# Development and Prospects of Terahertz Photodetector

Tianyu Li*

School of Precision Instrument and Opto-electronics Engineering Tianjin University Tianjin, 300000, China

*3019202329@tju.edu.cn

**Abstract.** Terahertz photodetectors show great potential in the fields of optical communication, security inspection, and nondestructive testing. This paper firstly outlines the properties of terahertz waves; further describes the detection mechanism and preparation materials; further discusses its applications in security inspection imaging through packaging materials, indoor local area wireless communication, high speed local area communication, space communication and confidential communication; finally summarizes and outlooks, the possible development directions of terahertz photodetectors are to study new materials with excellent optoelectronic properties at room temperature, to combine different sizes or different kinds of materials combined, the use of antennas to improve the coupling efficiency of terahertz radiation, and the design of new device structures. It can be foreseen that terahertz technology will have a profound impact on science and technology, economy and national security.

**Keywords:** Terahertz, photodetector, optical communication, non-destructive testing.

## 1. Introduction

Terahertz technology has shown great research potential in the fields of wireless communication, nondestructive testing, biosensing, and microscopic imaging, among which terahertz photodetection is considered to be one of the most promising fields and has been widely studied in recent years [1].

This paper firstly outlines the properties of terahertz waves and the development history of terahertz photodetectors; and further provides a brief introduction to the detection mechanism and preparation materials of terahertz photodetectors. The current applications of terahertz photodetectors in the fields of security inspection, nondestructive testing and communication are analyzed, and the new development prospects of terahertz photodetectors are discussed; the entire research is then summarized, and predictions are given on how terahertz photodetectors will evolve and be used in the future.

The huge application prospect of terahertz photodetector makes it strategically important in the future development of high technology, so governments attach great importance to the development of terahertz technology.

## 2. Theoretical foundations

### 2.1. Terahertz wave properties

Terahertz waves, which commonly refer to the frequency range of 0.1 terahertz to 10 terahertz, are a broad name for a particular band of electromagnetic waves that sit between millimeter and infrared waves in the electromagnetic spectrum. Figure 1 shows the location of terahertz waves in the range of electromagnetic waves.

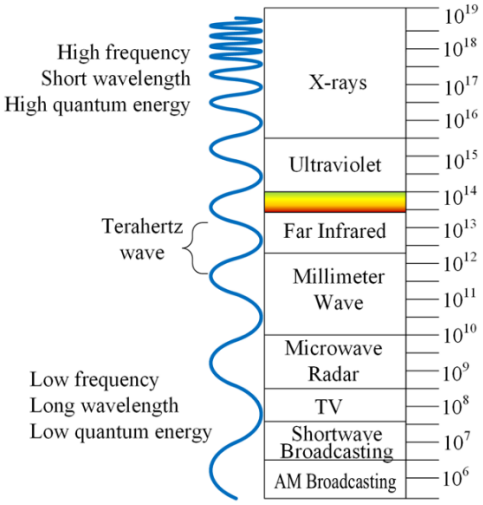



**Figure 1.** Terahertz Wave Position in the **Electromagnetic** Spectrum (Photo/Picture credit: Original)

Scientists only recently discovered terahertz waves in the electromagnetic spectrum, but the early unreliability and instability of terahertz radiation sources severely constrained the advancement of terahertz technology. This resulted in the terahertz band being less studied and was once called the "gap" in the electromagnetic spectrum.

Terahertz has attracted considerable research interest in recent years because, in addition to being a relatively lagging research band in the electromagnetic spectrum, it has a number of unique properties relative to other bands of electromagnetic waves.

First, in terms of transmittance, it is impressive how well terahertz waves penetrate certain non-metallic materials and non-polar liquids. Second, in terms of safety, terahertz waves have almost no effect on biological cells and are very safe for biological tissues. In addition, in terms of spectral resolution capability, terahertz waves have a high spectral resolution and spectral analysis is one of the most important applications of terahertz. Finally, high bandwidth is also an important feature of terahertz waves, because terahertz waves are the highest frequency electromagnetic waves that can be achieved by electrical means.

## 2.2. Development of terahertz photodetectors

In the last thirty years, terahertz detectors have developed rapidly, as shown in Figure 2, with an increasingly diverse range.

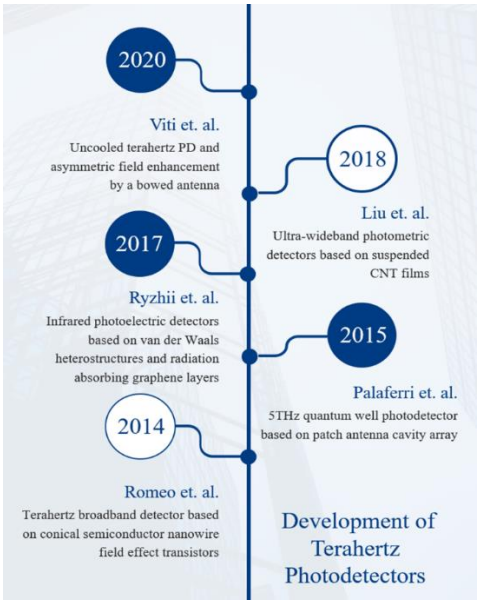



**Figure 2.** Development of Terahertz Photodetectors (Photo/Picture credit: Original)

However, the development of devices is inseparable from the development of materials, and to prepare high-performance terahertz detectors, it is first necessary to select suitable materials. In addition, during the development of terahertz detectors, the device structure of terahertz detectors has also undergone a change from simple to complex, and their performance and integration have been greatly improved.

Romeo et al. studied terahertz broadband detectors based on tapered semiconductor nanowire field-effect transistors [2]. The following year, Palaferri et al. developed a patch antenna cavity array-based 5 THz quantum well photodetector [3]. A graphene-layer infrared photodetector based on the van der Waals heterostructure was created by Ryzhii et al. in 2017 after they studied this structure [4]. Liu and colleagues looked at ultrabroadband photodetectors built on suspended CNT films in 2018 [5]. The mechanism of asymmetric field augmentation of uncooled terahertz PD and bent antennas was investigated by Viti et al. in 2020 [6].

### 2.3. Terahertz photodetector physical mechanism

#### 2.3.1. The detection mechanism of terahertz photodetectors

##### 2.3.1.1. Outlier detection

By combining the RF detection signal ($V_{RF}$) with a local oscillation signal ($V_{LO}$) at a nearby frequency, terahertz transmissions can be detected. The non-linear I-V characteristic is typically used for outlier detection, resulting in an intermediate frequency (IF) component in the output [7].

$$V_{IF} = | V_{RF} - V_{LO} | \tag{1}$$

Outlier detection is frequently employed in terahertz real domain spectroscopic imaging because it takes use of the high spectral resolution of terahertz waves and has a high sensitivity. In addition, outlier identification is high frequency selective, which allows for extremely effective use of a specific frequency band in electronics (i.e., the ability to accommodate numerous channels for signal transmission) and high spectral resolution in spectroscopy. Additionally, by selecting a detection bandwidth that is similar to that of narrow signals, noise may then be reduced due to the small detection range of outlier detection.

#### 2.3.2. Thermal detection

Terahertz radiation is absorbed by the absorber layer of the detector, which generates heat. The detecting material experiences a physical change that can be measured as a result of the change in heat, and terahertz may be detected utilizing this physical change. Because of the time needed to absorb the heat changes in the material during the thermal detection process, thermal detectors frequently have a rather sluggish response time. However, the reaction time is quicker but the cost is greater for some specialized superconducting and semiconductor heat detectors. Thermal detectors frequently detect a broad-spectrum range since heat is produced whenever terahertz radiation strikes the absorber layer, which is a benefit of thermal detection [8].

#### 2.3.3. Photoconductive detection

It can be noted that photons carry lower energy at terahertz frequencies, which is usually related to the energy difference between the conduction or valence bands of a semiconductor. When the energy of the photon exceeds the band gap of the semiconductor, intrinsic excitation occurs and changes the conductivity. Intrinsic excitation occurs when the energy of the photon exceeds the band gap of the semiconductor. Even if the photons lack the energy needed to cross the band gap, it is still sometimes possible to induce photoconductive processes by adding impurities to the semiconductor. Because the emitting or accepting state is very close to the valence band of the semiconductor, low frequency photons can stimulate the electrons to achieve the transition between the emitting and accepting states.

### 2.3.4. Photovoltaic detection

Potential barrier photodetectors are another name for photovoltaic terahertz detectors that are largely based on the photogenerated volt effect. When terahertz radiation is absorbed by the device, excited photogenerated carriers are injected close to the potential barrier, generating a photogenerated voltage. Terahertz detectors, a common type of photovoltaic device, have been intensively researched using devices in the form of field effect crystals. The detection of terahertz signals is made possible by field-effect transistor (FET) terahertz photodetectors, which utilise the plasma resonance concept to produce photogenerated voltages. Plasma waves can regulate the dynamic properties of short-channel field-effect transistors at terahertz frequencies when the carrier mobility is high enough. These collective plasma oscillations can be seen in double-quantum-well field-effect transistors with periodic grating gates and two-dimensional electron channels with reverse-biased Schottky junctions. In an electron gas in two dimensions (2DEG), the frequency of the plasma mode can be represented as $\omega_o$ with the value given in the following equation:

$$\omega_o = \frac{\pi}{2L}\sqrt{\frac{e(V_g - V_{th})}{m}} \tag{2}$$

where $L$ refers to the gate size, $V_g$ to the gate power, $V_{th}$ to the cutoff power and m to the real mass of the electron. Field effection plasma detectors rely on the collective oscillation of the electron gas and thus can provide a new strategy for developing outstanding performance ambient temperature terahertz detection. By reducing the channel size and making um-scale gate lengths, the resonant frequency of multifaceted plasma oscillations in the field effection transistor can be increased to the terahertz range. By adjusting the gate power, the field-effect transistor can be directly applied to both non-resonant (broadband) and resonant (specific wavelength range) terahertz detection. In addition, the parasitic capacitance of the electron channel modulated by the gate voltage has less influence on the cutoff frequency and sensitivity, enabling the development of more sensitive broadband terahertz detectors in the future.

## 2.4. Materials for the preparation of terahertz photodetectors

Conventional materials for terahertz detectors are mainly based on group III A-V and group IV A semiconductor materials. Photoconductive detectors generally use some low-temperature growth materials, such as GaAs and InP; radiometric thermometers are mainly InSb, Si and Ge; pyroelectric detectors use crystals with pyroelectric properties, such as $LiTaO_3$, $LiNbO_3$, DTGS (deuterated triglycopeptide sulfate) and so on. Nowadays, with the development of material preparation technologies, some novel substances with extremely desirable optoelectronic performance have been used to the preparation of teraherton detectors, such as one-dimensional carbon nanotubes, graphene, transition metal disulphides, black phosphorus, topological insulator materials and some other two-dimensional materials.

One-dimensional materials like carbon nanotubes have received a lot of interest since they were discovered in 1991 because of their potential uses in industries like biosensing and optoelectronic detection. According to their structural makeup, carbon nanotubes may be divided into three types: single-walled, double-armed, and multi-walled.

Additionally, graphene may be employed to create quick-responding room-temperature photodetectors because to its great carrier mobility. Additionally, graphene is the perfect photosensitive material for broadband terahertz detectors due to its zero-bandgap energy band structure. At this time, terahertz detectors are constructed using single-layer, bilayer, and multilayer graphene, all of which have demonstrated satisfactory working performance at room temperature.

Layers of the novel semiconductor material known as perovskite disulphides (TMDs) maintain stability by van der Waals forces. TMDs are readily joined to other materials by van der Waals interactions and exhibit strong non-linear optical response characteristics and high carrier mobilities.

## 3. Characteristics and applications of terahertz photodetectors

### 3.1. Safety Inspection

The photon energy of terahertz waves is relatively low and can theoretically be used for security screening. Currently, terahertz human security screening devices have been used in the security screening of some major conferences and events. Due to the high responsiveness of terahertz imaging, the use of terahertz security checkers in train stations and other places with a high flow of people can greatly improve the efficiency of security checks. The strong transmission capability and low radiation energy of terahertz meet the significant national needs in public safety detection, such as detection of drugs and firearms, which makes terahertz security monitoring expected to be a new public safety monitoring technology. Since terahertz can be used for both imaging and spectral analysis, and its penetration capability is extremely high, it can be used to achieve non-contact and non-destructive detection, which can be well applied to homeland defense. Terahertz imaging technology will soon replace current security screening techniques in public locations including airports, train stations, and customs [9].

In reality, since the 1970s, methods for nondestructive imaging employing continuous radiation in the Asia-Pacific Hertz band have been studied. As a bridge between visible light and microwaves, some opaque materials suitable as dielectrics at visible and near-infrared light frequencies have a very low percentage of absorption at terahertz frequencies. RF, microwaves, and X-rays can also pass through these materials transparently, but terahertz radiation has a better spatial resolution due to its shorter wavelengths than the other two. Terahertz radiation is also less dangerous to people than X-rays. As a result, for safe imaging, the terahertz area of the electromagnetic spectrum offers a compromise between spatial resolution and penetration depth. The development of semiconductor technology to the point where usable systems may be created has just recently occurred. The Terahertz imaging systems is shown in figure 3.

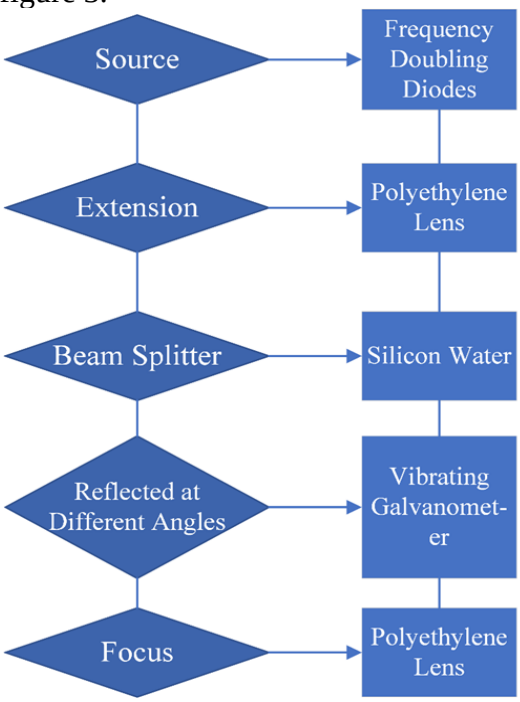



**Figure 3.** Terahertz Imaging Systems (Photo/Picture credit: Original)

### 3.2. Non-destructive detection

Terahertz inspection has unique advantages over other NDT techniques for detecting internal defects in non-metallic materials. The high transmittance of terahertz waves to non-polar materials allows the detection of internal defects that are not detectable by visible light. It can also be used for adiabatic materials, for which thermal imaging is difficult to function properly, thus making up for

the lack of thermal imaging. Compared to commonly used particle rays, terahertz waves are very low in energy and provide higher contrast. Compared to ultrasound, terahertz waves can achieve internal imaging without touching the surface of the object. And in some materials where acoustic waves decay rapidly, the advantages of terahertz waves are even more pronounced. Terahertz pulse imaging has also been used to detect defects in space shuttle isolation layer foam materials. The time domain waveform of each part is obtained by scanning point by point, and then the changes in the waveform are analyzed to determine the size, shape, location and type of defects. Terahertz nondestructive testing has important application prospects. The non-destructive testing technology flow chart is shown in figure 4 [10].

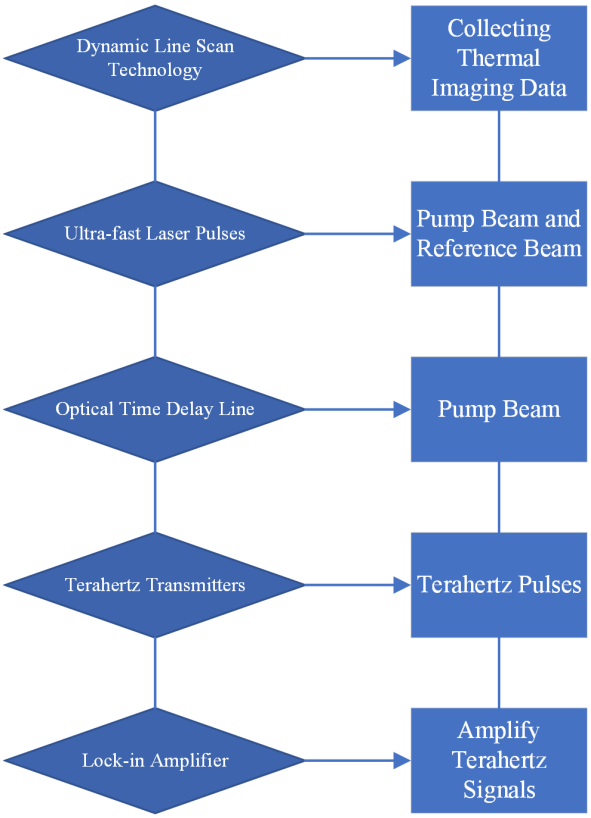



**Figure 4.** Non-destructive Testing **Technology** Flow Chart (Photo/Picture credit: Original)

### 3.3. Communications

Researchers have discovered that the utilization of terahertz frequencies for radar and telecommunication applications is severely constrained by atmospheric opacity. However, because to their great speed and security, terahertz communications are particularly well suited for local area communications, especially in the field. Numerous close-range devices have been suggested and researched as terahertz technology has advanced. Secure communications involve the tiny antenna size required to create highly directed beams and the enormous information bandwidth permitted by terahertz carriers due to the significant attenuation in the target receiver area. It is demonstrated that numerous significant atmospheric transparency windows may be used to provide high-capacity close-range terahertz communications by utilizing the low-frequency portion of the terahertz band. Terahertz communications and radar systems perform better in the stratosphere because to the lower scattering compared to infrared and optical wavelengths. Terahertz communications can also be a good fit for interstellar satellite-to-satellite communications because water vapor is almost nonexistent in space. Figure 5 displays the communication scenarios for several airplanes [11,12].

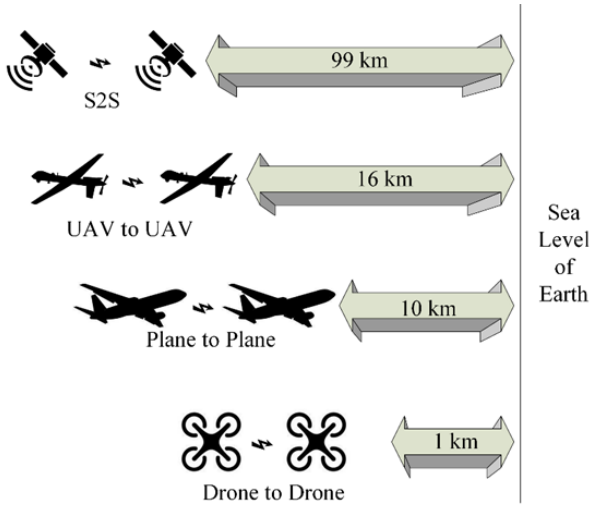



**Figure 5.** Communication Cases for Different Aircraft (Photo/Picture credit: Original)

The communication bands for different aircraft is shown in figure 6.

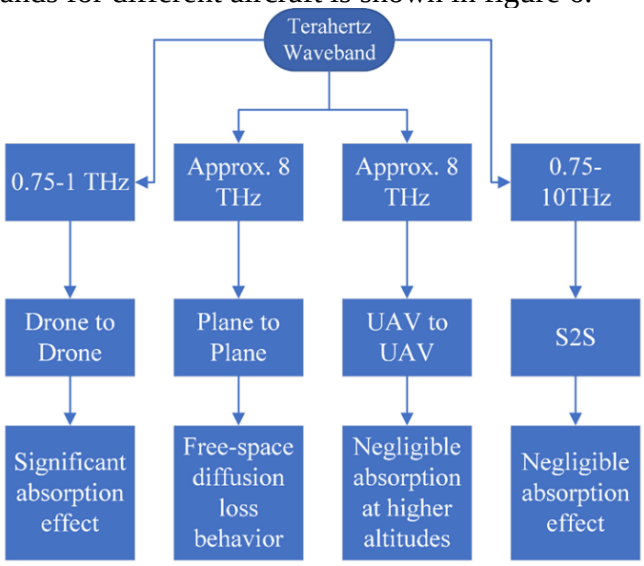



**Figure 6.** Communication Bands for Different Aircraft (Photo/Picture credit: Original)

In general to avoid larger absorption losses at sea level, the transmission rate of sea level communication decreases significantly with increasing transmission distance. Following this, we believe that drone to drone (D2D) communications is the lowest case for airborne communications because drones are used for various applications such as disaster recovery or military purposes and because terahertz band communications can provide high bandwidth at this altitude to exchange high resolution images or video. Jet aircraft, which typically soar to heights of around 10,000 meters, may be another real-world example of terahertz communications. Finally, terahertz bands can provide extremely fast communication links between high-altitude drones, which typically operate at altitudes of a few kilometers or less. Terahertz has previously been used for satellite communications at an altitude known as the Kamen space frontier, or about 100 kilometers [13,14].

## 4. Conclusion

Due to the nature of terahertz waves, the properties of different terahertz materials are often different, and the detection principles used may be different, so the device forms of terahertz detectors are very diverse, and terahertz photodetectors have been able to be used in many research applications, showing great promise for applications, while increasing the demand for high efficiency and low detection limit detection. Terahertz detectors are now widely used for non-destructive testing, safety

testing and proximity communication, but there is still much room for progress in terms of detection sensitivity and communication distance.

The development of terahertz photodetector has made significant breakthroughs in recent years, but still cannot meet the market demand, and the current laboratory-level terahertz detectors are still a long way from commercialization. Now the terahertz detector can detect the frequency is basically in the low frequency of the terahertz band, it is difficult to achieve the detection of high frequency terahertz band, to achieve a stable adjustable frequency terahertz photodetector more difficult. Currently, possible directions for the development of terahertz photodetectors include: research on new materials with excellent optoelectronic properties at room temperature to develop room-temperature terahertz detectors; combining different dimensions or different kinds of materials to complement each other; using antennas to enhance the coupling efficiency to terahertz radiation to enhance its responsivity; and designing new device structures, such as terahertz detectors in the form of field-effect transistors.

## References

[1] A. Y. Pawar, D. D. Sonawane, K. B. Erande, and D. V. Derle, "Terahertz technology and its applications," Drug Invention Today, vol. 5, no. 2, pp. 157–163, Jun. 2013.

[2] L. Romeo et al., "Terahertz photodetectors based on tapered semiconductor nanowires," Applied Physics Letters, vol. 105, no. 23, p. 231112, Dec. 2014.

[3] D. Palaferri et al., "Patch antenna terahertz photodetectors," APPLIED PHYSICS LETTERS, vol. 106, no. 16, pp. 161102–161102, Apr. 2015.

[4] V. Ryzhii et al., "Nonlinear response of infrared photodetectors based on van der Waals heterostructures with graphene layers," OPTICS EXPRESS, vol. 25, no. 5, pp. 5536–5536, May 2017.

[5] Y. Liu et al., "High-Performance, Ultra-Broadband, Ultraviolet to Terahertz Photodetectors Based on Suspended Carbon Nanotube Films," ACS APPLIED MATERIALS & INTERFACES, vol. 10, no. 42, pp. 36304–36311, Sep. 2018.

[6] L. Viti, D. M. Purdie, A. Lombardo, A. Ferrari, and M. S. Vitiello, "HBN-Encapsulated, Graphene-based, Room-temperature Terahertz Receivers, with High Speed and Low Noise," NANO LETTERS, vol. 20, no. 5, pp. 3169–3177, Apr. 2020.

[7] J. Yang, H. Qin, and K. Zhang, "Emerging terahertz photodetectors based on two-dimensional materials," Optics Communications, vol. 406, pp. 36–43, Jan. 2018.

[8] A. Rogalski, "Infrared detectors: status and trends," Progress in Quantum Electronics, vol. 27, no. 2–3, pp. 59–210, Jan. 2003.

[9] Q. Song, Y. Zhao, A. Redo-Sanchez, C. Zhang, and X. Liu, "Fast continuous terahertz wave imaging system for security," Optics Communications, vol. 282, no. 10, pp. 2019–2022, May 2009.

[10] J. Hu et al., "Non-destructive imaging of marqueteries based on a new infrared-terahertz fusion technique," Infrared Physics & Technology, vol. 125, pp. 104277–104277, Jun. 2022.

[11] P. H. Siegel, "Terahertz technology," IEEE Transactions on Microwave Theory and Techniques, vol. 50, no. 3, pp. 910–928, Mar. 2002.

[12] M. J. Fice, E. Rouvalis, L. Ponnampalam, C. C. Renaud, and A. J. Seeds, "Telecommunications technology-based terahertz sources," Electronics Letters, vol. 46, no. 26, p. S28, 2010.

[13] I. F. Akyildiz, J. M. Jornet, and C. Han, "Terahertz band: Next frontier for wireless communications," Physical Communication, vol. 12, pp. 16–32, Sep. 2014.

[14] A. Saeed, O. Gurbuz, and M. A. Akkas, "Terahertz communications at various atmospheric altitudes," Physical Communication, vol. 41, p. 101113, Aug. 2020.